TECHNICAL REPORT

AMRA TR 63-04

ON THE ORIGIN OF THE EARTH'S MAGNETIC FIELD

by

R. J. WEISS

MATERIALS RESEARCH LABORATORIES

U. S. ARMY MATERIALS RESEARCH AGENCY

FEBRUARY 1963 WATERTOWN 72, MASS.

#1.50

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Terrestrial magnetism

Earth

Ferromagnetism

Iron

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February 1963

MRL Report 131

AMS Code 5026.11.842

D/A Project 1-H-0-24401-A-110

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ABSTRACT

It is suggested that the inner core of the earth may be a new high pressure phase of iron. The observed density is in accord with a phase transition presumed to be associated with the transfer of two of the "3p" electrons of the "argon-core" of atomic iron to the "3d-4s" band. The high pressure phase would be ferromagnetic and have an estimated Curie temperature of about 5500°K. The earth's magnetic field would arise from the residual magnetization of the unmagnetized ferromagnetic core. Magnetostrictive effects can cause variations in magnitude and direction of this field. Planets with small mass would not develop the pressures required and would have no magnetic fields.

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*Work performed while a guest of the Department of Mathematics, Imperial College, London, under a Secretary of the Army's Research and Study Fellowship.

ON THE ORIGIN OF THE EARTH'S MAGNETIC FIELD

From a knowledge of the mass of the earth and its moment of inertia and from an analysis of seismic data Bullen[1] has reconstructed a pressure-density curve for the earth's interior. The outer core of the earth is believed to be liquid since it does not transmit transverse seismic waves while the structure of the inner core is still in doubt. The entire core is believed to be predominantly iron.

According to Bullen the interface between the inner and outer cores occurs at a depth of $\sim$5000 km. corresponding to a pressure of $\sim 3.3 \times 10^{12}$ dynes/cm^2, a temperature of $\sim 4000^\circ$K and a density of $\sim$11.5 g/cm^3 in the outer core and $\sim$15.2 g/cm^3 in the inner core. It is the purpose of this note to suggest that the inner core may well be a new phase of iron in which two of the 3p "argon core" electrons are transferred to the "3d-4s" band and that such a phase may account for the origin of the earth's magnetic field.

That the above values of density, pressure and temperature for the *outer core* are reasonable for iron comes from a knowledge of the compressibility of iron and its pressure dependence[2] $K = -(1/V)(dV/dP) = 5.8 \times 10^{-13}$ (cm^2/dynes) $\times$ $(1 - 2 \times 10^{-13} P$ cm^2/dynes$) = a(1 - bP)$ and an approximate value of the coefficient of volume expansion $\alpha = (1/V)(dV/dT) \cong 80 \times 10^{-6}$/deg. This gives the density, ρ,

$$\rho(P,T) \cong \rho(0,0) \exp\{aP(1 - bP/2)\} \exp\{-\alpha T\}$$

where $\rho(0)$ is the extrapolated density of liquid iron at $P = 0$, $T = 0$ leading to a value

$$\rho(P,T) \cong 11.2 \text{ g/cm}^2 \text{ (at the inner-outer core interface)}$$

in good agreement with Bullen's estimate. However the density change in iron is only 3.5% on melting so that the $\sim$30% change at the interface suggested by Bullen (11.5 g/cm^3 versus 15.2 g/cm^3) appears too large to attribute to *normal solidification of iron in the inner core*. On the other hand the transfer of two of the 3p electrons to the 3d-4s band would add two more electrons to the six bonding electrons (the two magnetic electrons are in antibonding states) and in analogy to the cases of the rare earth metals cerium, europium, and ytterbium this would change the atomic volume approximately in proportion to the number of overlapping electrons. In iron this new high pressure phase would correspond to a density change of $\sim$25%.

That the transfer of one or two electrons from the 3p shell to the overlapping "3d-4s" band is energetically feasible comes from an estimate of the band width and the one electron energy eigenvalues of the 3p electrons. Because of the large overlap of the "3d-4s" electrons at these high pressures we can use free electron theory to give us an approximate value of the band width and this gives ~55 eV for the inner core as compared to 69 eV* for the Hartree-Fock one electron 3p energy.[3] (In analogy to the rare earth metals thulium, ytterbium, and lutecium we suggest that two rather than one electron will be transferred from the inner closed shell although this point is not critical to our argument).

Because of the very strong spin orbit coupling the remaining four electrons in the 3p shell will probably couple according to Hund's rule leaving two unpaired electrons with L = 1, S = 1, J = 2. In order to estimate the Curie temperature of this new phase we need to estimate the exchange energy. While such a straightforward calculation is beyond the current capabilities of solid state physics an approximate value can be obtained *relative* to the ordinary form of ferromagnetic iron for which we have experimental values of the exchange energy.[4] Since the exchange energy arises from the overlap of the band electrons with the unpaired atomic-like electrons we wish to estimate the exchange integral

$$J \alpha \left| \int \psi_A(r_1)\psi_B(r_2) \frac{e^2}{r_{12}} \psi_A(r_2)\psi_B(r_1)\, d\tau \right|^2 / E_F \qquad (1)$$

where the subscript A denotes the unpaired atomic-like electron wave function and the subscript B the overlapping band electron wave function and E_F is the Fermi energy. For the normal ferromagnetic form of iron these are the unpaired 3d and the "3d-4s" band electrons respectively while for our postulated high pressure form of iron these are the 3p and the "3d-4s" band electrons respectively. Since the overlapping electrons at the bottom of the band in iron are extended quite far radially[5] we can assume ψ_B is constant throughout the atomic cell for both the normal and high pressure phases. This term alone would lead to a ratio of ~6.5 for the values of J in the high pressure and normal phases while the Fermi energy in the denominator (55 eV versus ~10 eV) reduces this to ~1.2. This leaves the evaluation of the r_{12} term for the unpaired 3p and 3d electrons respectively and this must surely be greater for the former since they are more compressed radially. It is estimated that their contribution to J would lead to a ratio approximately of the order of their one electron energies (- 5.3 Rydbergs versus - 1.3 Rydbergs) or about a factor of 4. This roughly gives an overall factor of 4 for the ratio of J in the high pressure and normal phases or a value of 0.04 eV for the high pressure phase.**

From statistical mechanics a close packed structure with nearest neighbor exchange interactions (S = 1) has a value of J/kT_c = 0.08 leading to an estimated value of the Curie temperature of our high pressure form

$$T_c \cong J/0.08k = 5500\,^\circ K$$

which is well above the inner-outer core interface temperature of ~4000°K.

**The X-ray absorption edge in metallic iron corresponding to a transition from the 3p level to the Fermi level occurs at 53 eV.*

***If we apply equation 1 to the normal cases of ferromagnetic iron and gadolinium where in the latter case ψ_A refers to the 4f electrons, one obtains a ratio of ~40 for the J values as compared to the observed value of ~50.*

If this crude order of magnitude estimate is correct there are several consequences of note:

1. If the planets contain cores similar in composition to the earth only those of mass approximately equal to or greater than the earth would develop sufficient gravitational pressure to create the high pressure magnetic phase. Thus we would expect no magnetic field on Mercury, Mars, Venus, and the moon but would expect magnetic fields on Uranus, Neptune, Saturn and Jupiter.

2. If the inner core were saturated (a single magnetic domain) the magnetic field at the earth's surface would be about $\sim$150 gauss. The observed value of $\sim$1 gauss is thus typical of the residual magnetization of an unmagnetized piece of iron.

3. Magnetostrictive effects (spin-orbit coupling) can cause variations in the magnitude and direction of the earth's magnetic field depending on the variation of the distribution of pressure on the surface of the inner core. Because the anisotropy energy is small compared to the compressional energy only small changes in pressure are necessary to effect changes in magnetic domain orientation.

4. Inasmuch as static pressures of $\sim 0.5 \times 10^{12}$ dynes/cm^2 have been reached in the laboratory[6] it is probable that materials and techniques will improve sufficiently to reach this suggested critical pressure of $\sim 3.5 \times 10^{12}$ dynes/cm^2 for the onset of the high pressure magnetic phase of iron. Thus our hypothesis is probably capable of laboratory refutation.

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